COMPACT AND EASY-OPERATION MAGNETOCARDIOGRAPH WITH FOUR-CHANNEL PLANAR GRADIOMETERS

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Abstract-**A magnetocardiograph (MCG), which consists of a sensor comprising four superconducting-quantum-interference device (SQUID) gradiometers and a magnetic shielding cylinder made of nanocrystalline soft magnetic materials, has been developed. The sensor can be handled easily because the gradiometers are made of high-critical-temperature (Tc) superconductor operated in liquid nitrogen. Further, the shielding cylinder is lightweight (160 kg) and compact (2 m long and 1 m in diameter). The gradiometer balance is high enough (typically 0.1%) for recording magnetocardiograms inside the shielding cylinder, whose shielding factor is –35 dB at 1 Hz.**

We used the new MCG to record magnetocardiograms of a healthy volunteer at four different positions. From this magnetocardiograms we then obtained a current arrow map, by which mycardium activity can be estimated, at 16 sites (4 × 4 matrix) on the measurement plane. The similarity between the current-arrow map obtained by a conventional MCG and that from the newly developed MCG indicates that the developed compact MCG is also capable of estimating the region of cardiac activity.

***Keywords* - SQUID, high-Tc, shielding, magnetocardiograph**

I. INTRODUCTION

A magnetocardiograph (MCG) is an instrument that can noninvasively record and visualize mycardium activity by measuring magnetic fields generated by human hearts. MCG has been applied to diagnosis of ischemic [1, 2] or fetal [3] heart disease and estimation of the region of arrhythmia [4]. In the conventional MCG [5], superconducting-quantum-interference devices (SQUIDs) made of low-critical-temperature (Tc) superconductors are employed, so they must be operated in liquid helium. The difficulty in handling liquid helium and the huge, heavy (2 × 2 × 2 m and 2000 kg) magnetic shielding room needed obstruct the wide spread use of MCG. High-Tc SQUIDs [6] can solve the former problem because they can be operated in liquid nitrogen.

We have already developed high-Tc SQUID gradiometers [7] and a magnetic shield cylinder [8]. In the current work, we fabricated lightweight, compact, and easy-to-operate MCG (four-channel) and demonstrated its capability for estimating the region of mycardium activity.

II. METHOD

The fabricated MCG consists of the following components (Fig. 1): a magnetic shielding cylinder in which a patient lies, a dewar and four high-Tc SQUID gradiometers, conventional ac-biased (128 kHz) flux-locked-loop (FLL) circuits to drive the SQUIDs, a FLL controller, a conventional electrocardiograph (ECG), a filter unit, and a 1-kHz sampling data storage. The shielding cylinder and the SQUID gradiometer are described below briefly.

A. Magnetic shielding cylinder

The fabricated MCG measures the normal component (z-direction) of the magnetic field, B_z, to the measurement (x-y) plane parallel to the patient's chest. The open-ended shielding cylinder by which magnetic fields perpendicular to the axis (x- and z-directions) are shielded is suitable for this measurement, although the shielding factor of the field parallel to the axis (y-direction) is low. The cylinder is 2 m long, 1 m in diameter, and weighs 160 kg. The shielding is provided by flexible sheets made of 20-μm-thick FINEMET® (Fe-Cu-Nb-Si-B nanocrystalline soft magnetic material [9]) ribbon sandwiched between two polyethylene terephthalate (PET) films. The shielding cylinder consists of three shielding shells made of

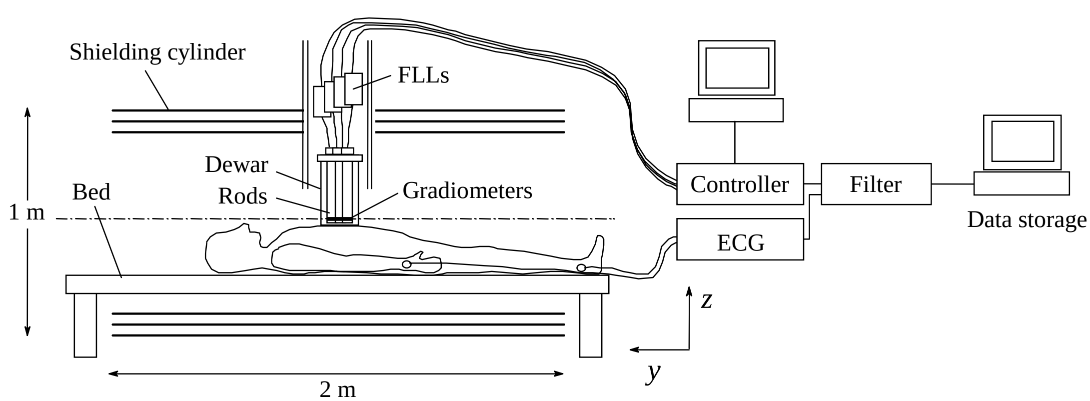

Fig. 1. Schematic diagram of the developed magnetocardiograph.

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0.5-mm-thick aluminum cylinders 50 mm apart, and the sheets are stuck on the aluminum cylinders in 6-, 6-, and 14-sheet-thick layers (from outside to inside). The measured shielding factors in the x- and z-directions at the center of the cylinder are better than –35 dB under a low-frequency (1-90 Hz) range [8].

B. Sensor

The dewar for holding liquid nitrogen is small (300 mm in height) and has four ports for inserting sensing rods whose centers are 46 mm apart. Each rod supports the high-Tc SQUID gradiometer at the bottom (Fig. 3). Each gradiometer (planar type) was fabricated from $YBa_2Cu_3O_y$ films on a 15 × 15-mm $SrTiO_3$ bicrystal substrate (Fig. 4(a)). There are two pickup coils and four SQUIDs (Fig. 4(b)) in each gradiometer. The differential shielding supercurrent between the two pickup coils flows in the four SQUIDs. Hence, by connecting one of the SQUIDs to the FLL, each gradiometer can measure magnetic field gradient, $\Delta B_z/\Delta x$ or $\Delta B_z/\Delta y$, while it reduces uniform environmental magnetic field noise. The baseline length which is defined as the distance between the pickup coils, i.e., Δx or Δy, is estimated to be 6.75 mm.

The balance between the pickup coils of each gradiometer, which determines noise reduction ratio, is extremely high (typically 0.1 %) [7]. Moreover, the cross-talking ratio, which is defined as the ratio of the detected field gradient to the applied field gradient on the pickup coils of the next gradiometer, was measured to be less than 2×10^{-6}. Both the balance and the cross-talking ratio are sufficient for recording magnetocardiograms.

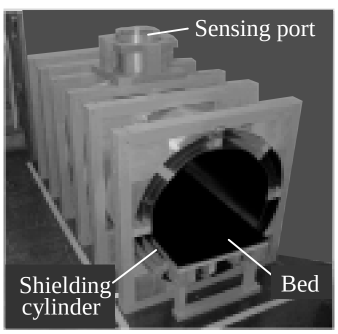

Fig. 2. Photograph of the magnetic shielding cylinder.

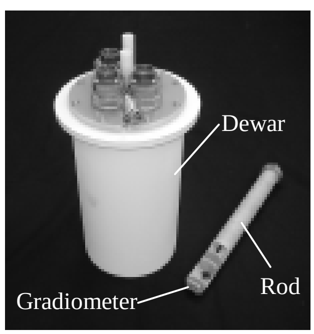

Fig. 3. Photograph of the dewar and one of the interior rods supporting a high-Tc SQUID gradiometer.

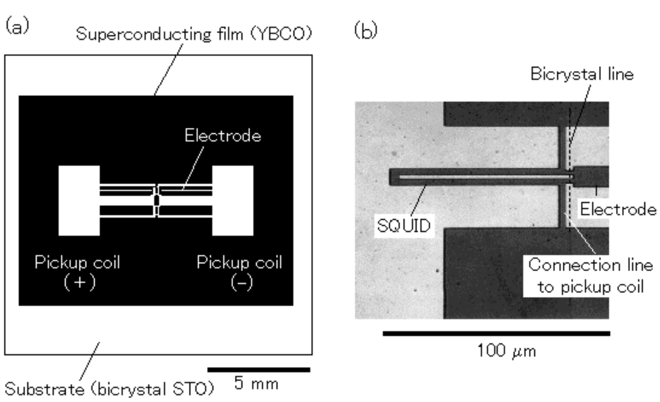

Fig. 4. Structure of the fabricated high-Tc SQUID gradiometer (a) and photograph of the area around one of the SQUIDs (b).

III. Results and Discussion

A. Noise

The noise spectra of the gradiometers located inside (Fig. 5(a)) and outside (Fig. 5(b)) the shielding cylinder are compared with that of the environmental magnetic field noise (Fig. 5(c)). The noise measured by the gradiometer was converted to field noise from gradient noise by multiplying it by the baseline length. It is reduced to –57 dB (0.14 %) at 1 Hz by the gradiometric structure. It is reduced a further –25 dB (5.7 %) to –82 dB by the shielding effect of the cylinder from environmental noise. Because the shielding factor of the cylinder is better than –35 dB, the noise of the inside gradiometer is apparently limited by the intrinsic noise of the gradiometer itself. Magnetocardiograms were obtained under the noise condition in Fig. 5(a).

B. Magnetocardiograms

Magnetocardiograms of a healthy volunteer were obtained by the four-channel MCG (Fig. 6). They were passed through 0.1-30 Hz band pass and 50-, 100-, and 150-Hz notch filters to remove power-line noise, then averaged over 100 beats by the ECG. The gradient direction was selected by rotating each rod individually. The QRS-complex and T-wave were traced clearly. The peak-to-peak noise, $B_{n\ \text{p-p}}$, is equivalent to or less than 0.2 nT/m estimated from $B_{n\ \text{p-p}} = CB_n\sqrt{W}$ [10], where C is a constant around 4, B_n is the white noise shown in Fig. 5, and W is the bandwidth.

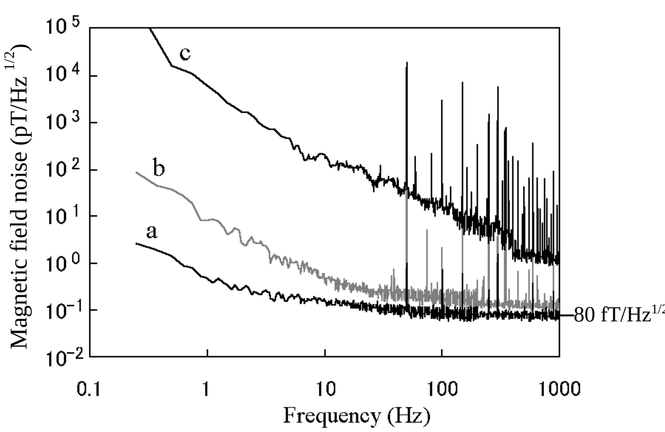

Fig. 5. Magnetic-field-noise spectra measured by one of the fabricated gradiometers inside (a) and outside (b) the shielding cylinder. The environmental noise is also shown (c).

C. Current arrow map

The current arrow, vector ***i***, at each site is calculated from $\boldsymbol{i}=(\Delta B_z/\Delta y, -\Delta B_z/\Delta x)$ [11]. Current arrow maps can be regarded as projections on the measurement plane of a cardiac-current distribution [12].

We recorded magnetocardiograms under the same conditions described in the previous section at four different positions (Fig. 7), then we calculated current arrows at 16 sites (4 × 4 matrix) at a 46-mm pitch. The obtained arrows superimposed on the contour maps, which show the iso-magnitude of the current vector ***i***, illustrate temporal change of the most active regions (Fig. 8; a part of QRS-complex in 5-ms intervals).

To verify the obtained current arrow maps, we compared them to those of the same volunteer measured by a conventional MCG with low-Tc SQUID gradiometers (MC-6400, Hitachi, Ltd.) [5]. The conventional MCG measures z-gradient of normal components, $\Delta B_z/\Delta z$, at 64 sites (8 × 8 matrix) at a 25-mm pitch. The current arrows are reconstructed by spatial subtraction of the magnetocardiograms. The mapping area of the conventional MCG (175 × 175 mm) is slightly larger than that of the new MCG (138 × 138 mm) (Fig. 7), whose current distributions (Fig. 8) are similar to those of the conventional MCG (Fig. 9), although the sensing pitch is wider. Similar results were observed regarding the T-wave region.

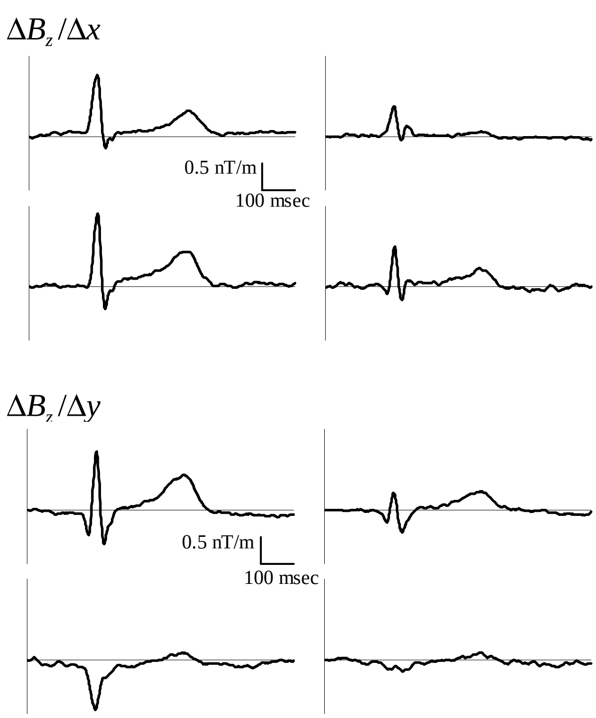

Fig. 6. Examples of magnetocardiograms. Gradients of normal component in x-direction, $\Delta B_z/\Delta x$, and y-direction, $\Delta B_z/\Delta y$ are measured by the four channels.

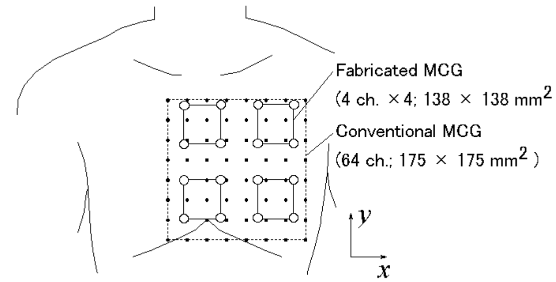

Fig. 7. Measurement areas and detection sites of the developed (open circles) and conventional MCGs (dots).

V. CONCLUSION

The similarity between the current-arrow map obtained by a conventional MCG and that from the newly developed MCG indicates that the developed compact MCG is also capable of estimating the region of cardiac activity.

To improve the MCG, it is essential to increase the number of channels (finally around 50 channels). And, because the noises of the gradiometers are limited by their intrinsic noise at present, the intrinsic noise must be reduced (or the baseline length must be larger to increase the signals). For example, two to three-times bigger signal-to-noise ratio would make it possible to observe the P-wave without averaging [13]. These improvements, together with its lightness, compactness, and ease of use, will enable the new MCG to be applied to clinical diagnosis extensively.

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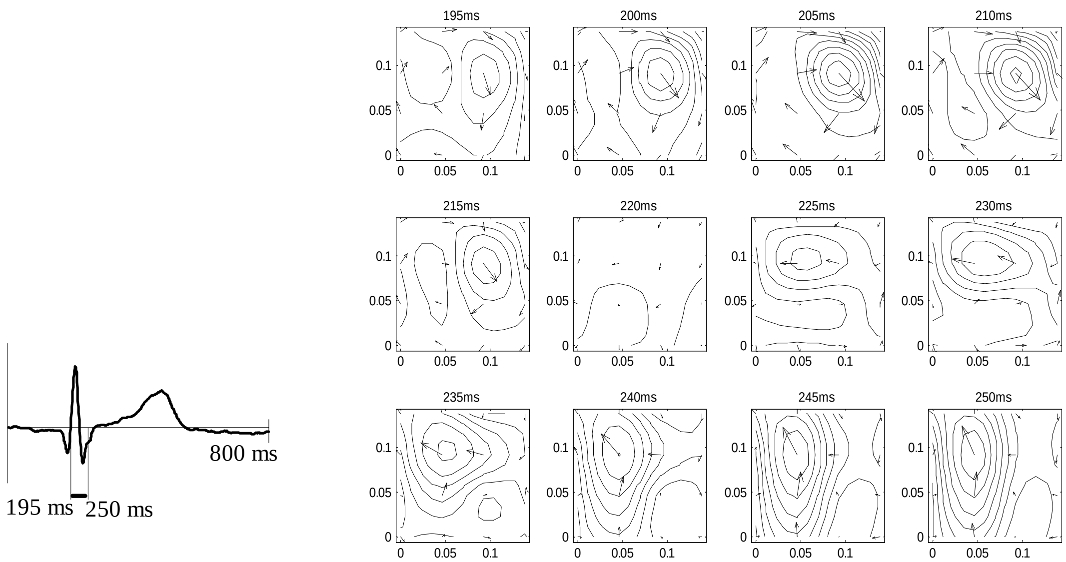

Fig. 8. Current arrow map representing the QRS-complex of a healthy volunteer obtained by using the developed MCG.

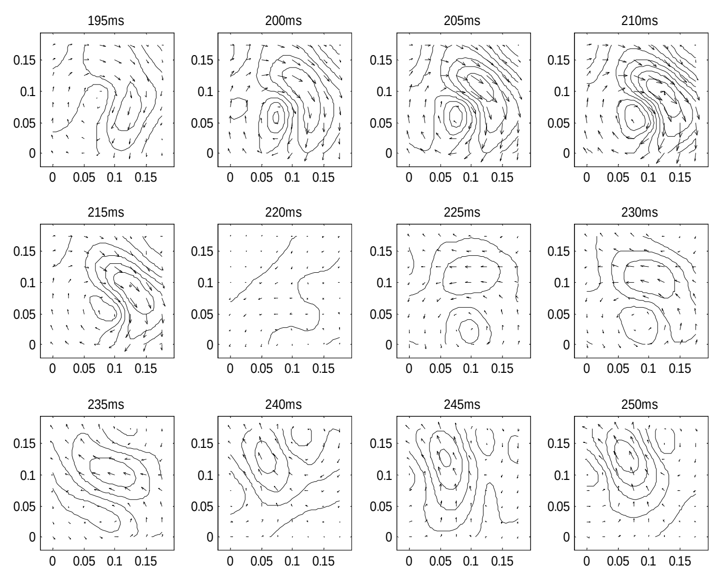

Fig. 9. Current arrow map representing the QRS-complex of the same volunteer obtained by using a conventional MCG.